

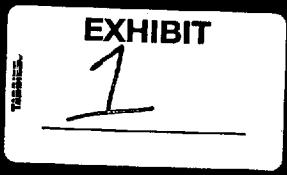
S C I E N C E

PHYSICS

for Scientists and Engineers

WITH MODERN PHYSICS

THIRD EDITION



**UPDATED
VERSION**

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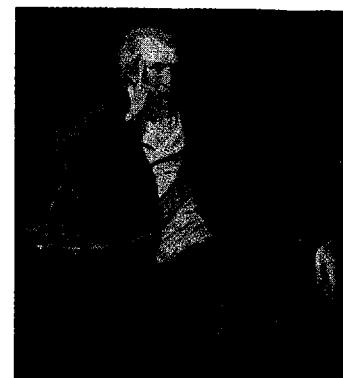
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during the boring process. On the basis of the caloric theory, he reasoned that the ability of the metal filings to retain caloric should decrease as the size of the filings decreased. These heated filings, in turn, presumably transferred caloric to the cooling water, causing it to boil. To his surprise, Thompson discovered that the amount of water boiled away by a blunt boring tool was comparable to the quantity boiled away by a sharper tool for a given turning rate. He then reasoned that if the tool were turned long enough, an almost infinite amount of caloric could be produced from a finite amount of metal filings. For this reason, Thompson rejected the caloric theory and suggested that heat is not a substance, but some form of motion that is transferred from the boring tool to the water. In another experiment, he showed that the heat generated by friction was proportional to the mechanical work done by the boring tool.

There are many other experiments that are at odds with the caloric theory. For example, if you rub two blocks of ice together on a day when the temperature is below 0°C , the blocks will melt. This experiment was first conducted by Sir Humphry Davy (1778–1829). To properly account for this “creation of caloric,” we note that mechanical work is done on the system. Thus, we see that the effects of doing mechanical work on a system and of adding heat to it directly, as with a flame, are equivalent. That is, heat and work are both forms of energy transfer.

Although Thompson’s observations provided evidence that heat energy is not conserved, it was not until the middle of the 19th century that the modern mechanical model of heat was developed. Before this period, the subjects of heat and mechanics were considered to be two distinct branches of science, and the law of conservation of energy seemed to be a rather specialized result used to describe certain kinds of mechanical systems. After the two disciplines were shown to be intimately related, the law of conservation of energy emerged as a universal law of nature. In this new view, heat is treated as another form of energy that can be transformed into mechanical energy. Experiments performed by the Englishman James Joule (1818–1889) and others in this period showed that whenever heat is gained or lost by a system during some process, the gain or loss can be accounted for by an equivalent quantity of mechanical work done on the system. Thus, by broadening the concept of energy to include heat as a form of energy, the law of energy conservation was extended.



Benjamin Thompson (1753–1814). “Being engaged, lately, in superintending the boring of cannon, in the workshops of the military arsenal at Munich, I was struck with the very considerable degree of Heat which a brass gun acquires in a short time, in being bored; and with the still more intense Heat (much greater than that of boiling water, as I found by experiment) of the metallic chips separated from it by the borer.”

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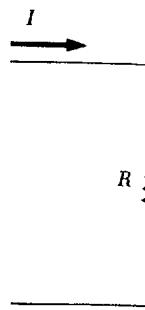


temperatures are nperature of the e cooler body in- eventually reach a e two initial tem- nsferred from the at transfer? Early substance called According to this hough the caloric ly was abandoned tot conserved. oric was not con- end of the 18th to Europe during following his ap- n the title Count non in Munich, e boring tool. The as it boiled away

20.1 HEAT AND THERMAL ENERGY

There is a major distinction between the concepts of heat and the internal energy of a substance. The word *heat* should be used only when describing energy transferred from one place to another. That is, *heat flow is an energy transfer that takes place as a consequence of temperature differences only*. On the other hand, *internal energy* is the energy a substance has because of its temperature. In the next chapter, we shall show that the energy of an ideal gas is associated with the internal motion of its atoms and molecules. In other words, the internal energy of a gas is essentially its kinetic energy on a microscopic scale; the higher the temperature of the gas, the greater its internal energy. As an analogy, consider the distinction between work and energy that we discussed in Chapter 7. The work done on (or by) a system is a measure of energy transfer between the system and its surroundings, whereas the mechanical energy (kinetic and/or potential) is a consequence of the motion and

Definition of heat



circuit consisting if \mathcal{E} and resistance rge flows in the on, from the nega-
ve terminal of the
a and *d* are

Consider a simple circuit consisting of a battery whose terminals are connected to a resistor R , as shown in Figure 27.15. The symbol $\text{---} \mid$ is used to designate a battery (or any other direct current source), and resistors are designated by the symbol $\text{---} \wedge \text{---}$. The positive terminal of the battery (the longer plate) is at the higher potential, while the negative terminal (the shorter plate) is at the lower potential. Now imagine following a positive quantity of charge ΔQ moving around the circuit from point *a* through the battery and resistor and back to *a*. Point *a* is a reference point that is grounded (ground symbol $\text{---} \perp$), and its potential is taken to be zero. As the charge moves from *a* to *b* through the battery, its electrical potential energy *increases* by an amount $V\Delta Q$ (where V is the potential at *b*) while the chemical potential energy in the battery *decreases* by the same amount. (Recall from Chapter 25 that $\Delta U = q\Delta V$.) However, as the charge moves from *c* to *d* through the resistor, it *loses* this electrical potential energy as it undergoes collisions with atoms in the resistor, thereby producing thermal energy. Note that if we neglect the resistance of the interconnecting wires there is no loss in energy for paths *bc* and *da*. When the charge returns to point *a*, it must have the same potential energy (zero) as it had at the start.⁶

The rate at which the charge ΔQ *loses* potential energy in going through the resistor is given by

$$\frac{\Delta U}{\Delta t} = \frac{\Delta Q}{\Delta t} V = IV$$

where I is the current in the circuit. Of course, the charge regains this energy when it passes through the battery. Since the rate at which the charge loses energy equals the power P lost in the resistor, we have

$$P = IV \quad (27.21)$$

In this case, the power is supplied to a resistor by a battery. However, Equation 27.21 can be used to determine the power transferred to *any* device carrying a current I and having a potential difference V between its terminals.

Using Equation 27.21 and the fact that $V = IR$ for a resistor, we can express the power dissipated in the alternative forms

$$P = I^2R = \frac{V^2}{R} \quad (27.22)$$

When I is in amperes, V in volts, and R in ohms, the SI unit of power is the watt (W). The power lost as heat in a conductor of resistance R is called *joule heating*⁷; however, it is often referred to as an I^2R loss.

A battery or any other device that provides electrical energy is called an *electromotive force*, usually referred to as an *emf*. The concept of emf will be discussed in more detail in Chapter 28. (The phrase *electromotive force* is an unfortunate one, since it does not describe a force but actually refers to a potential difference in volts.) Neglecting the internal resistance of the battery, the potential difference between points *a* and *b* is equal to the emf \mathcal{E} of the

⁶ Note that when the current reaches its steady-state value, there is *no* change with time in the kinetic energy associated with the current.

⁷ It is called *joule heating* even though its dimensions are *energy per unit time*, which are dimensions of power.

battery. That is, $V = V_b - V_a = I = V/R = \mathcal{E}/R$. Since $V = \mathcal{E}$, the as $P = I\mathcal{E}$, which, of course, equ

EXAMPLE 27.7 Power in an Electric Heater
An electric heater is constructed to make a temperature difference of 110 V to a nichrome wire of length 8 m and cross-sectional area 8Ω . Find the current carried by the wire.

Solution Since $V = IR$, we have

$$I = \frac{V}{R} = \frac{110 \text{ V}}{8 \Omega} =$$

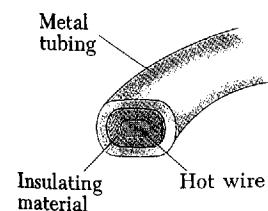
We can find the power rating using

$$P = I^2R = (13.8 \text{ A})^2(8 \Omega)$$

If we were to double the applied voltage, the current would double but the power would increase by a factor of four.

27.8 ENERGY CONVERSION IN CIRCUITS

The heat generated when current passes through a resistor is used in many common devices. A cross-section of a heating element in an electric range is shown in Figure 27.16. When current passes through the wire, the current passes through the wire, which is surrounded by an insulating material. A metal tube surrounds the wire.



(a)

Figure 27.16 (a) The cross-section of a heating element in an electric range. Warm air is produced by blowing air over the hot wire, which is surrounded by an insulating material and enclosed in a metal tube.